Flow Rate Measurement for Industrial Sensing
Applications Using Unsteady Pressures

Cross References to Related Applications

5   This application is an continuation-in-part of commonly owned co-pending US Patent Applications, Serial No., 09/346,607, entitled "Flow Rate Measurement Using Unsteady Pressures", filed July 2, 1999.

Technical Field

10   This invention relates to the measurement of flow rate of a fluid and more particularly to measuring flow rate using unsteady pressure measurements for use in industrial sensing applications.

Background Art

.   An industrial process sensor is typically a transducer that responds to a measurand

15   with a sensing element and converts the variable to a standardized transmission signal, e.g., an electrical or optical signal, that is a function of the measurand. Industrial process sensors utilize transducers that include flow measurements of an industrial process such as that derived from slurries, liquids, vapors and gasses in refinery, chemical, paper, pulp, petroleum, gas, pharmaceutical, food, mining, minerals and other fluid processing plants.

20   Industrial process sensors are often placed in or near the process fluids, or in field applications. Often, these field applications are subject to harsh and varying environmental conditions that provide challenges for designers of such sensors. Flow measurement is one of the largest segments of the industrial sensing and instrumentation market. Industries in which flow measurement is prevalent includes petroleum, chemical, pulp, paper, food, and

25   mining and minerals.

In many industries it is desirable to measure the flow rate of a multiphase fluid. In many industries such as refinery, chemical, paper, pulp, petroleum, gas, pharmaceutical, food, mining, minerals or comparable industries, for example, it is desirable to measure the flow rate of multiphase fluids, especially fluids having three phases, such as a constituent,

30   water and gas. It is known also to measure the flow rate of certain fluids (one or more liquids and/or gases) in a pipe using cross-correlation flow meters. Such meters measure an element of the flow that moves or convects with (or is related to) the fluid flow (or a group of fluid particles). The meter measures this element at two locations separated by a known

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distance along the flow path and then calculates the time for such element to move between the two locations. The time delay is determined by a cross-correlation of the two measured signals. A velocity is then determined by the distance between the measurements divided by the time delay. The flow velocity is then related to the flow rate by calibration.

5   One such cross-correlation meter that measures flow rate in a multiphase flow is described in US Patent No. 5,591,922, entitled "Method and Apparatus for Measuring Multiphase Flow", to Segeral et al, issued Jan. 7, 1997. In that case, a pair of venturis are located a predetermined distance apart which induce a change in flow speed through the venturi and a resulting pressure difference (or delta-P) across each venturi, which are

10   measured. The delta-P pressure signals measured at each venturi are cross-correlated to determine the time delay which is indicative of the total volume flow rate. However, such a technique requires a change in the flow properties (e.g., flow velocity or density) at the two measurement points to make the measurement. Also, the delta-P is generated with an area contraction or constriction, and is not a naturally occurring observable characteristic of the

15   fluid.

Other flowmeters of the prior art include turbine, vortex, electromagnetic and venturi and all have drawbacks and deficiencies solved by the flowmeter of the present invention. For instance all require a high level of maintenance and need to be removed from the process line wherein the operators need to shut down the manufacturing process.

20   The flowmeters of the prior art require electrical wiring and power that requires enormous cost, safety issues and sometimes miles of wires. May of the prior art meters use moving parts, such as turbines or diaphragms. Also, prior art flowmeters such as vortex, turbine and venturi types use obstructions in the flow path that disrupt the flow to varying degrees. In addition sediment, gumming, plugging, corrosion, and erosion of certain features of the

25   sensing region of the meter can affect the accuracy of the flowmeter.

In particular, electromagnetic flowmeters are prone to problems caused by poor process grounding, and specialized sleeves that prone to damage. Process noise is a problem and can be caused by slurries, high consistency pulp stock, or upstream chemical additions. Such process noise can lead to inaccurate flow measurement in these types of

30   prior art flowmeters. In addition, process liquids must have a minimum conductivity that all but eliminates these meters from uses where the fluid is a hydrocarbon . The accuracy and sensitivity can be affected by the length of cabling for remote transmitters and can be adversely influenced by proximity to other electrical devices

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Another flow meter of the prior art includes a friction flowmeter such as that set forth in US Patent No. 6,253,624, titled "Friction Flowmeter" wherein a transducer determines the pressure drop of a fluid flowing along a pipe. The device determines the flow rate of the fluid based on the pressure drop for a given friction factor of the inside surface of the pipe. Such a device requires external knowledge of various parameters of the fluid, such as density. In addition, with certain applications the surface of the pipe, and the friction factor thereby, would change over time and decrease the accuracy of the meter in predicting fluid flow rates.

Typical electronic, or other, transducers of the prior art often cannot be placed in industrial process environments due to sensitivity to electro-magnetic interference, radiation, heat, corrosion, fire, explosion or other environmental factors. It is for these reasons that fiber optic based sensors are being incorporated into industrial process control environments in increasing number.

Summary of the Invention

Objects of the present invention include provision of a system for measuring the flow rate (or velocity) of fluid flow in pipes in industrial fluid processes.

According to the present invention, an apparatus for use in an industrial process for measuring a velocity of a fluid moving in a pipe, comprises a first filter which measures a vortical pressure field at a first axial location along the pipe which provides a first pressure signal indicative of the vortical pressure field; and a second filter which measures the vortical pressure field at a second axial location along the pipe which provides a second pressure signal indicative of the vortical pressure field. The invention further comprises a signal processor, responsive to the first and the second pressure signals, which provides a velocity signal indicative of a velocity of the vortical pressure field moving in the pipe.

According further to the present invention, the first and the second filters passes wavelengths associated with the vortical pressure field and not associated with an acoustic pressure field. According further to the present invention, the first filter comprises a first spatial filter; and the second filter comprises a second spatial filter. According still further to the present invention, the vortical pressure field comprises a homogeneous pressure field. Still further according to the present invention, the first and the second filters pass wavelengths associated with the vortical pressure field and not associated with an acoustic pressure field. According further to the present invention, the spatial filter filters out

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wavelengths above a predetermined wavelength. Still further according to the present invention, at least one of the pressure sensors comprises a strain gage disposed on a surface of the pipe. Further according to the present invention, the strain gage comprises a fiber optic strain gage.

5   Still further according to the present invention, the signal processor comprises logic which calculates a cross-correlation between the first and the second inhomogeneous pressure signals and provides a time delay signal indicative of the time it takes for the vortical pressure field to move from the first location to the second location. Further according to the present invention, the velocity signal is indicative of the velocity of the

10   fluid moving in the pipe.

        The present invention provides a significant improvement over the prior art by providing a measurement of the average flow rate of fluid flow in a pipe or other conduit (where a fluid is defined as one or more liquids and/or gases) without requiring a flow restriction in the pipe or any other change in the flow velocity of the fluid.

15   The present invention determines a convection velocity by measuring unsteady (or dynamic or ac) pressures and extracting the pressure signal indicative of a vortical pressure (or flow) field (or perturbation) which convects at or near the average velocity of the fluid. The vortical pressure field is then used to determine the convection velocity by cross-correlation techniques, such convection velocity being proportional (or approximately equal

20   to) the flow rate of the fluid. If needed, the flow rate of the fluid may then be determined by calibrating the convection velocity to the flow rate.

        The invention may also be used to measure the velocity of any inhomogeneous flow field, such as gas bubbles, gas slugs, particles, or chunks of material, and its associated pressure field that propagates in a flow provided the spatial filters have a separation within

25   the acceptable coherence length of the flow field to be measured and the sensor spacing within each spatial filter is longer than a characteristic axial length of the flow field. Also, the invention may be used to detect different flow rates within the same mixture (e.g., the flow rate of a vortical pressure field as well as other inhomogeneous pressure fields).

        Also, the invention may be used with any combination of liquids and/or gases and

30   may include particles. The invention will also work in any other environment or applications or any other fluids (one or more liquids and/or gases) or mixtures. The invention will work with any pipe or tube or with any conduit that carries fluid. Also, the invention has no inherent flow range limitations, and, as such, can measure very low flow

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rates and has no maximum flow rate limit. The invention will also work if the fluid is flowing in either direction in the pipe. Further, the invention may be used directly on a pipe or on a tube inserted into a flowing fluid.

Also, the invention may be combined with a controller and other devices and used in an industrial process control system.

The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof.

Brief Description of the Drawings

Fig. 1 is a schematic block diagram of a velocity measurement system, in accordance with the present invention.

Fig. 2 is a side view of a pipe having two sensors that measure a parameter that convects with the flow in the pipe, in accordance with the present invention.

Fig. 3 is a graph of two curves, one from each of the two sensors of Fig. 2, in accordance with the present invention.

Fig. 4 is a graph of a cross-correlation between the two curves of Fig. 3, in accordance with the present invention.

Fig. 5 is a graph of power spectral density plotted against frequency for an unsteady acoustic pressure signal $P_{acoustic}$ and unsteady vortical pressure signal $P_{vortical}$, in accordance with the present invention.

Fig. 6 is a graph of wavelength versus frequency for unsteady acoustic pressures $P_{acoustic}$ and unsteady vortical pressures $P_{vortical}$, in accordance with the present invention.

Fig. 7 is a graph of power spectrum of two unsteady pressures and the difference between the two pressures, in accordance with the present invention.

Fig. 8 is a graph of a cross-correlation between two of the curves of Fig. 7, in accordance with the present invention.

Fig. 9 is a graph of measured velocity against reference velocity, in accordance with the present invention.

Fig. 10 is a side view of a pipe having three pairs of unsteady pressure sensors spaced axially along the pipe, in accordance with the present invention.

Fig. 11 is a graph of a cross correlation coefficient versus time delay for the three pairs of sensors, in accordance with the present invention.

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Fig. 12 is a graph of measured flow rate against reference flow rate for various different mixtures, in accordance with the present invention.

Fig. 13 is an end view of a pipe showing pressure inside and outside the pipe, in accordance with the present invention.

Fig. 14 is a side view of a pipe having optical fiber wrapped around the pipe at each unsteady pressure measurement location and a pair of Bragg gratings around each optical wrap, in accordance with the present invention.

Fig. 15 is a side view of a pipe having optical fiber wrapped around the pipe at each unsteady pressure measurement location with a single Bragg grating between each pair of optical wraps, in accordance with the present invention.

Fig. 16 is a side view of a pipe having optical fiber wrapped around the pipe at each unsteady pressure measurement location without Bragg gratings around each of the wraps, in accordance with the present invention.

Fig. 17 is an alternative geometry of an optical wrap of Figs. 14,15&16, of a radiator tube geometry, in accordance with the present invention.

Fig. 18 is an alternative geometry of an optical wrap of Figs. 14,15&16, of a race track geometry, in accordance with the present invention.

Fig. 19 is a side view of a pipe having a pair of gratings at each axial sensing location, in accordance with the present invention.

Fig. 20 is a side view of a pipe having a single grating at each axial sensing location, in accordance with the present invention.

Fig. 21 is a side view of a pipe having two pairs of pressure sensors where the sensors in each pair are located across the pipe from each other, in accordance with the present invention.

Fig. 22 is an end view of a pipe showing a pair of pressure sensors located at various circumferential spacings from each other, in accordance with the present invention.

Fig. 23 is a side view of a pipe having two pairs of pressure sensors where the sensors in each pair are located transversely across the pipe and spaced axially along the pipe from each other, in accordance with the present invention.

Fig. 24 is a side view of a pipe having a set of three pressure sensors that form a spatial filter, in accordance with the present invention.

Fig. 25 is a side view of a pipe having an inner tube with axially distributed optical fiber wraps for unsteady pressure sensors, in accordance with the present invention.

Fig. 26 is a side view of a pipe having an inner tube with axially distributed unsteady pressure sensors located along the tube, in accordance with the present invention.

Fig. 27 is a side view of a pipe having an inner tube with four axially distributed optical fiber wrapped hydrophones located within the tube, in accordance with the present invention.

Fig. 28 is an end view of a pipe showing a pair of pressure sensors spaced apart from each other within the pipe, in accordance with the present invention.

Fig. 29 is a side view of a pipe having a pair of unsteady pressure sensors spaced axially within the pipe, in accordance with the present invention.

Fig. 30 is a side view of a pipe having a pair of unsteady pressure sensors spaced transversely within the pipe, in accordance with the present invention.

Fig. 31 is a side view of a pipe having a pair of unsteady pressure sensors axially and radially spaced within the pipe, in accordance with the present invention.

Fig. 32 is a side view of a pipe having a set of three pressure sensors that make up two spatial filters, in accordance with the present invention.

Fig. 33 is a schematic drawing of a flow meter in an industrial process control system, in accordance with the present invention.

Fig. 34 is a plan view of alternate geometries for electronic strain gages in accordance with the present invention.

Fig. 35 is a side view of a pipe having a spatial filter disposed thereon comprised of electronic strain gages in accordance with the present invention.

Best Mode for Carrying Out the Invention

Referring to Fig. 1, a velocity and flow measurement system includes a sensing section 10 along a pipe 12 and a velocity logic section 40. The pipe (or conduit) 12 has two measurement regions 14,16 located a distance ΔX apart along the pipe 12. At the first measurement region 14 are two unsteady (or dynamic or ac) pressure sensors 18,20, located a distance X_1 apart, capable of measuring the unsteady pressure in the pipe 12, and at the second measurement region 16, are two other unsteady pressure sensors 22,24, located a distance X_2 apart, capable of measuring the unsteady pressure in the pipe 12. Each pair of pressure sensors 18,20 and 22,24 act as spatial filters to remove certain acoustic signals from the unsteady pressure signals, and the distances X_1, X_2 are determined by the desired filtering characteristic for each spatial filter, as discussed hereinafter.

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The flow measurement system 10 of the present invention measures velocities associated with unsteady flow fields and/or pressure disturbances represented by 15 associated therewith relating to turbulent eddies (or vortical flow fields), inhomogeneities in the flow (such as bubbles, slugs, and the like), or any other properties of the flow, fluid, or pressure, having time varying or stochastic properties that are manifested at least in part in the form of unsteady pressures. The vortical flow fields are generated within the fluid of the pipe 12 by a variety of non-discrete sources such as remote machinery, pumps, valves, elbows, as well as the fluid flow itself. It is this last source, the fluid flowing within the pipe, that is a generic source of vortical flow fields primarily caused by the shear forces between the fluid and the wall of the pipe that assures a minimum level of disturbances for any fluid piping systems for which the present invention takes unique advantage. The flow generated vortical flow fields generally increase with mean flow velocity and do not occur at any predeterminable frequency. As such, no external discrete vortex generating source is required within the present invention and thus may operate using passive detection. It is within the scope of the present that the pressure sensor spacing may be known or arbitrary and that as few as two sensors are required if certain information is known about the acoustic properties of the system as will be more fully described herein below.

The vortical flow fields 15 are, in general, comprised of pressure disturbances having a wide variation in length scales and which have a variety of coherence length scales such as that described in the reference "Sound and Sources of Sound", A. P.Dowling et al, Halsted Press, 1983. Certain of these vortical flow fields convect at or near/or related to the mean velocity of at least one of the fluids within a mixture flowing in a pipe. More specifically, the vortices convect in a predictable manner with reference to the fluids. The vortical pressure disturbances 15 that contain information regarding convection velocity have temporal and spatial length scales as well as coherence length scales that differ from other disturbances in the flow. The present invention utilizes these properties to preferentially select disturbances of a desired axial length scale and coherence length scale as will be more fully described hereinafter. For illustrative purposes, the terms vortical flow field and vortical pressure field will be used to describe the above-described group of unsteady pressure fields having temporal and spatial length and coherence scales described herein.

The pressures P_1, P_2, P_3, P_4 may be measured through holes in the pipe 12 ported to external pressure sensors or by other techniques discussed hereinafter. The pressure sensors 18,20,22,24 provide time-based pressure signals $P_1(t), P_2(t), P_3(t), P_4(t)$ on lines 30,32,34,36,

respectively, to Velocity Logic 40 which provides a convection velocity signal $U_c(t)$ on a line 42 which is related to an average flow rate $U_f(t)$ of the fluid flowing in the pipe 12 (where fluid may comprise one or more liquids and/or gases; where the gas(es) may be dissolved in the liquid or in free gas form, such as bubbles, slugs, sand, particulates, slurry,

5   etc.), and wherein the fluid may include non-liquid elements therein as will be discussed more hereinafter.

Also, some or all of the functions within the Velocity Logic 40 may be implemented in software (using a microprocessor or computer) and/or firmware, or may be implemented using analog and/or digital hardware, having sufficient memory, interfaces, and capacity to

10   perform the functions described herein.

In particular, in the Velocity Logic 40, the pressure signal $P_1(t)$ on the line 30 is provided to a positive input of a summer 44 and the pressure signal $P_2(t)$ on the line 32 is provided to a negative input of the summer 44. The output of the summer 44 is provided on a line 45 indicative of the difference between the two pressure signals P_1, P_2 (e.g., P_1-

15   $P_2 = P_{as1}$).

The pressure sensors 18,20 together with the summer 44 create a spatial filter 33. The line 45 is fed to bandpass filter 46, which passes a predetermined passband of frequencies and attenuates frequencies outside the passband. In accordance with the present invention, the passband of the filter 46 is set to filter out (or attenuate) the dc portion and

20   the high frequency portion of the input signals and to pass the frequencies therebetween. For example, in a particular embodiment passband filter 6 is set to pass frequencies from about 1 Hz to about 100 Hz, for a 3 inch ID pipe flowing water at 10 ft/sec. Other passbands may be used in other embodiments, if desired. Passband filter 46 provides a filtered signal $P_{asf}1$ on a line 48 to Cross-Correlation Logic 50, described hereinafter.

25   The pressure signal $P_3(t)$ on the line 34 is provided to a positive input of a summer 54 and the pressure signal $P_4(t)$ on the line 36 is provided to a negative input of the summer 54. The pressure sensors 22,24 together with the summer 54 create a spatial filter 35. The output of the summer 54 is provided on a line 55 indicative of the difference between the two pressure signals P_3, P_4 (e.g., P_3-$P_4 = P_{as2}$). The line 55 is fed to a bandpass filter 56,

30   similar to the bandpass filter 46 discussed hereinbefore, which passes frequencies within the passband and attenuates frequencies outside the passband. The filter 56 provides a filtered signal $P_{asf}2$ on a line 58 to the Cross-Correlation Logic 50. The signs on the summers 44,54 may be swapped if desired, provided the signs of both summers 44,54 are swapped together.

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In addition, the pressure signals P_1, P_2, P_3, P_4 may be scaled prior to presentation to the summers 44,54.

The Cross-Correlation Logic 50 calculates a known time domain cross-correlation between the signals $P_{asf}1$ and $P_{asf}2$ on the lines 48,58, respectively, and provides an output signal on a line 60 indicative of the time delay τ it takes for an vortical flow field 15 (or vortex, stochastic, or vortical structure, field, disturbance or perturbation within the flow) to propagate from one sensing region 14 to the other sensing region 16. Such vortical flow disturbances, as is known, are coherent dynamic conditions that can occur in the flow which substantially decay (by a predetermined amount) over a predetermined distance (or coherence length) and convect (or flow) at or near the average velocity of the fluid flow. As described above, the vortical flow field 15 also has a stochastic or vortical pressure disturbance associated with it. In general, the vortical flow disturbances 15 are distributed throughout the flow, particularly in high shear regions, such as boundary layers (e.g., along the inner wall of the pipe 12) and are shown herein as discrete vortical flow fields 15. Because the vortical flow fields 15 (and the associated pressure disturbance) convect at or near the mean flow velocity, the propagation time delay τ is related to the velocity of the flow by the distance ΔX between the measurement regions 14,16, as discussed hereinafter.

Although pressure disturbances associated with vortical flow fields 15 occur naturally in most flow conditions, an optional circumferential groove 70 may be used in the inner diameter of the pipe 12 to help generate unsteady flow fields in the form of vertices into the flow. However, the groove 70 is not required for the present invention to operate, due to vortex generation which naturally occurs along the pipe inner wall, as discussed hereinbefore. Instead of a single circumferential groove 70 a plurality of axially spaced circumferential grooves may be used. The dimensions and geometry of the groove(s) 70 may be set based on the expected flow conditions and other factors. The axial cross-sectional shape of the groove 70 may be rectangular, square, triangular, circular, oval, star, or other shapes. Other techniques may be used as vortex generators if desired including those that may protrude within the inner diameter of pipe 12.

A spacing signal ΔX on a line 62 indicative of the distance ΔX between the sensing regions 14,16 is divided by the time delay signal τ on the line 60 by a divider 64 which provides an output signal on the line 42 indicative of the convection velocity $U_c(t)$ of the fluid flowing in the pipe 12, which is related to (or proportional to or approximately equal to) the average (or mean) flow velocity $U_f(t)$ of the fluid, as defined below:

$$U_c(t) = \Delta X / \tau \propto U_f(t) \qquad \qquad \text{Eq. 1}$$

The convection velocity $U_c(t)$ may then be calibrated to more precisely determine the mean velocity $U_f(t)$ if desired. The result of such calibration may require multiplying the value of the convection velocity $U_c(t)$ by a calibration constant (gain) and/or adding a

5   calibration offset to obtain the mean flow velocity $U_f(t)$ with the desired accuracy. Other calibration may be used if desired. For some applications, such calibration may not be required to meet the desired accuracy. The velocities $U_f(t), U_c(t)$ may be converted to volumetric flow rate by multiplying the velocity by the cross-sectional area of the pipe.

Referring to Figs. 2,3,4, as is known, cross-correlation may be used to determine the

10   time delay τ between two signals $y_1(t), y_2(t)$ separated by a known distance ΔX, that are indicative of quantities 80 that convect with the flow (e.g., density perturbations, concentration perturbations, temperature perturbations, vortical pressure disturbances, and other quantities). In Fig. 3, the signal $y_2(t)$ lags behind the signal $y_1(t)$ by 0.15 seconds. If a time domain cross-correlation is taken between the two signals $y_1(t), y_2(t)$, the result is

15   shown in Fig. 4 as a curve 84. The highest peak 86 of the curve 84 shows the best fit for the time lag τ between the two signals $y_1(t), y_2(t)$ is at 0.15 seconds which matches the reference time delay shown in Fig. 3.

Referring to Fig. 1, as discussed hereinbefore, since pressure disturbances associated within the vortical flow field 15 convect (or flow) at or near the average velocity of the fluid

20   flowing in the pipe 12, the vortical pressure disturbances observed at the downstream location 16 are substantially a time lagged version of the vortical pressure disturbances observed at the upstream location 14. However, the total vortical pressure perturbations or disturbances in a pipe may be expressed as being comprised of vortical pressure disturbances ($P_{vortical}$), acoustic pressure disturbances ($P_{acoustic}$) and other types of pressure

25   disturbances (P_{other}) as shown below expressed in terms of axial position along the pipe at any point in time:

$$P(x,t) = P_{vortical}(x,t) + P_{acoustic}(x,t) + P_{other}(x,t) \qquad \text{Eq. 2}$$

As a result, the unsteady pressure disturbances $P_{vortical}$ can be masked by the acoustic pressure disturbances $P_{acoustic}$ and the other types of pressure disturbances P_{other}. In

30   particular, the presence of the acoustic pressure disturbances that propagate both upstream and downstream at the speed of sound in the fluid (sonic velocity), can prohibit the direct measurement of velocity from cross-correlation of direct vortical pressure measurements.

The present invention uses temporal and spatial filtering to precondition the pressure signals to effectively filter out the acoustic pressure disturbances $P_{acoustic}$ and other long wavelength (compared to the sensor spacing) pressure disturbances in the pipe 12 at the two sensing regions 14,16 and retain a substantial portion of the vortical pressure disturbances

5     $P_{vortical}$ associated with the vortical flow field 15 and any other short wavelength (compared to the sensor spacing) low frequency pressure disturbances P_{other}. In accordance with the present invention, if the low frequency pressure disturbances P_{other} are small, they will not substantially impair the measurement accuracy of $P_{vortical}$.

The $P_{vortical}$ dominated signals from the two regions 14,16 are then cross-correlated

10   to determine the time delay τ between the two sensing locations 14,16. More specifically, at the sensing region 14, the difference between the two pressure sensors 18,20 creates a spatial filter 33 that effectively filters out (or attenuates) acoustic disturbances for which the wavelength λ of the acoustic waves propagating along the fluid is long (e.g., ten-to-one) compared to the spacing X_1 between the sensors. Other wavelength to sensor spacing ratios

15   may be used to characterize the filtering, provided the wavelength to sensor spacing ratio is sufficient to satisfy the two-to-one spatial aliasing Nyquist criteria.

Thus, if the pressure sensors P_1,P_2 have an axial spacing X_1, and assuming that the spatial filter 33 will attenuate acoustic wavelengths longer than about 10 times the sensor spacing X_1, the smallest acoustic wavelength λmin that is attenuated would be:

20     $$\lambda_{min} = 10 \ (X_1) \qquad \qquad \text{Eq. 3}$$

One dimensional acoustic disturbances are also governed by the following known inverse wavelength-frequency relation:

$$\lambda = a \ / \ f \ \text{ or } \ f = a \ / \ \lambda \qquad \qquad \text{Eq. 4}$$

where a is the speed of sound of the fluid, f is the frequency of the acoustic disturbance, and

25   λ is the wavelength of the acoustic disturbance.

Using Eq. 4, such a spatial filter would filter out frequencies below about:

$$f_{max} \ = \ a/\lambda_{min} \qquad \qquad \text{Eq. 5}$$

For example, using water (a = 5,000 ft/sec) with a sensor spacing X_1 = 3 inches, the above described spatial acoustic filtering would filter out acoustic frequencies up to a

30   maximum frequency of about 2000 Hz (or 5,000*12/30). Thus, the acoustic frequency content of the output signal P_{as1} of the spatial filter 33 (i.e., differenced vortical pressure signal) will be effectively removed for frequencies below about 2000 Hz and wavelengths above 30 inches (using Eq. 3).

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The above discussion on the spatial filter 33 also applies to the second spatial filter 35 comprising the other pair of pressure signals P_3,P_4, axially spaced a distance X_2 apart, which provides the differenced vortical pressure signal P_{as2}.

Referring to Fig. 5, relevant features of the power spectral density (PSD) of typical

5   vortical pressure disturbances $P_{vortical}$ is shown by a curve 90 that has a flat region (or bandwidth) up to a frequency F_v and then decreases with increasing frequency f. The value of F_v is approximately equal to U/r, where U is the flow rate and r is the radius of the pipe. For example, for a flow rate U of about 10 ft/sec and a pipe radius r of about 0.125 ft (or about 1.5 inches), the bandwidth F_v of the vortical pressure disturbances $P_{vortical}$ would be

10   about 80 Hz (10/0.125). The PSD of the acoustic pressure disturbances $P_{acoustic}$ has a profile that is determined by the environment and other factors and is indicated in the figure by an arbitrary curve 91, and typically has both low and high frequency components.

Referring to Fig. 6, in general, the acoustic pressure disturbances $P_{acoustic}$ have an inverse wavelength-frequency relationship as shown in Eq. 4, which has long wavelengths

15   at low frequencies and short wavelengths at high frequencies as indicated by the regions 96,98, respectively. Conversely, the vortical pressure disturbances $P_{vortical}$ have both long and short wavelengths as indicated by the regions 96,97, respectively; however, they exist primarily at low frequencies (as discussed hereinbefore with reference to Fig. 5). Thus, both $P_{acoustic}$ and $P_{vortical}$ exist in the long wavelength, low frequency region 96, and only $P_{vortical}$

20   exists in the short wavelength low frequency region 97.

The acoustic spatial filters 33,35 (Fig. 1) discussed hereinbefore block or attenuate wavelengths longer than λ_{as} and frequencies below f_{as}, as indicated by the region 96. Also, the bandpass filters (BPF) 46,56 (Fig. 1) block or attenuate high frequencies above f_{pb} having short and long wavelengths as indicated by a region 102 and pass frequencies below

25   f_{as} where the $P_{vortical}$ signals exist. Thus, after the spatial filters 33,35 and the BPF's 46,56, the resultant filtered signals P_{asf1}, P_{asf2} on the lines 48,58 (Fig. 1) will be dominated by the short wavelength unsteady pressure disturbances $P_{vortical}$ as indicated by the region 97 (Fig. 6) at frequencies below f_{pb} and as indicated by a portion 94 of the curve 90 in the BPF passband 95 (Fig. 5).

30   Accordingly, referring to Fig. 5, the spatial filters 33,35 (Fig. 1) block the long wavelengths, which, for the acoustic pressure disturbances $P_{acoustic}$, occur at low frequencies as indicated to the left of a dashed line 92 at frequencies below the frequency f_{as}. A dashed line 93 indicates the attenuation of the acoustic pressure $P_{acoustic}$ signal 91 below the

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frequency f_{as} at the output of the spatial filters. The vortical pressure disturbances $P_{vortical}$ are substantially not attenuated (or only slightly attenuated) because $P_{vortical}$ has short wavelengths at low frequencies that are substantially passed by the spatial filter. The BPF's 46,56 (Fig. 1) block or attenuate frequencies outside the passband indicated by a range of

5   frequencies 95, and passes the unsteady pressure disturbances associated with stochastic flow fields 15 (Fig. 1) within the passband 95.

Alternatively, instead of the filters 46,56 being bandpass filters, provided the dc content is acceptably small, the filters 46,56 may comprise low pass filters, having a bandwidth similar to the upper band of the high pass filters discussed hereinbefore. If a low

10   pass filter is used as the filters 46,56, the passband is shown as a range of frequencies 89. It should be understood that the filters 46,56 are not required for the present invention if the PSD of the acoustic pressure disturbances $P_{acoustic}$ has substantially no or low PSD energy content in frequencies above the stopband of the spatial filter that does not adversely affect the measurement accuracy.

15   Referring to Figs. 7 and 1, for the four ac pressure sensors 18,20,22,24 evenly axially spaced at 1 inch apart (X_1, X_2) along the pipe 12, and providing ac pressure signals P_1, P_2, P_3, P_4, respectively, the frequency power spectrum for P_1 and P_2 are shown by curves 100,102, respectively, for water flowing in an horizontal flow loop at a velocity of 11.2 ft/sec in a 2 inch diameter schedule 80 pipe using conventional piezoelectric ac pressure

20   transducers. The power spectra of the curves 100,102 are nearly identical. The power spectrum of the difference P_{as1} between the two signals P_1, P_2, shown by a curve 104 is reduced in certain frequency bands (e.g., 100-150 Hz) and increased in other frequency bands (e.g., 200-250 Hz) as compared to the individual signals 100,102.

Referring to Figs. 8 and 1, the cross correlation between the signals P_{as1} (or P_1-P_2)

25   and P_{as2} (P_3-P_4) is shown as a curve 110. The highest peak 112 indicates the best fit for the time lag between the two signals P_{as1}, P_{as2} as 0.015 seconds. Because the four sensors P_1 to P_4 were evenly axially spaced 1 inch apart, the effective distance ΔX between the sensor pairs is 2 inches. Thus, the velocity measured from Eq. 1 is 11.1 ft/sec (2/12/0.015) using the present invention and the actual velocity was 11.2 ft/sec.

30   Referring to Fig. 9, for the configuration described with Figs. 1,7,8 above, the velocity was measured at various flow rates and plotted against a reference velocity value. A solid line 120 shows the reference velocity, the triangles 122 are the measured data, and a

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line 124 is a curve fit of the data 122. This illustrates that the present invention predicts the flow velocity within a pipe (or conduit).

The pressure sensors 18,20,22,24 described herein may be any type of pressure sensor, capable of measuring the unsteady (or ac or dynamic) pressures within a pipe, such as piezoelectric, optical, capacitive, piezo-resistive (e.g., Wheatstone bridge), accelerometers, velocity measuring devices, displacement measuring devices, etc. If optical pressure sensors are used, the sensors 18-24 may be Bragg grating based pressure sensors, such as that described in copending US Patent Application, Serial No. 08/925,598, entitled " High Sensitivity Fiber Optic Pressure Sensor For Use In Harsh Environments", filed Sept. 8, 1997, now U.S. Patent 6,016,702. Alternatively, the sensors 18-24 may be electrical or optical strain gages attached to or embedded in the outer or inner wall of the pipe which measure pipe wall strain, including microphones, hydrophones, or any other sensor capable of measuring the unsteady pressures within the pipe 12. In an embodiment of the present invention that utilizes fiber optics as the pressure sensors 18-24, they may be connected individually or may be multiplexed along one or more optical fibers using wavelength division multiplexing (WDM), time division multiplexing (TDM), or any other optical multiplexing techniques (discussed more hereinafter).

Such harsh environments are typically found in the industrial process area and include sensor exposure to acids, caustics, nuclear energy, electromagnetic interference and exposure to explosive vapors among other hazards. Because the sensor is glass based it is chemically impervious to most industrial process related chemicals. Further because the sensor of the present invention uses light for signal transmission it does not require any electrical power and as such is not influenced by electromagnetic fields and cannot create arcing or explosions when used in the presence of flammable vapors. In addition the sensor of the present invention has no moving parts, such as a bellows, which makes the device more reliable and less susceptible to system hysteresis found in other mechanical pressure sensors that utilize diaphragms bellows or other displacement type devices.

Referring to Fig. 13, if a strain gage is used as one or more of the pressure sensors 18-24 (Figs. 14-20), it may measure the unsteady (or dynamic or ac) pressure variations P_{in} inside the pipe 12 by measuring the elastic expansion and contraction, as represented by arrows 350, of the diameter (and thus the circumference as represented by arrows 351) of the pipe 12. In general, the strain gages would measure the pipe wall deflection in any direction in response to unsteady pressure signals inside the pipe 12. The elastic expansion

and contraction of pipe 12 is measured at the location of the strain gage as the internal

pressure P_{in} changes, and thus measures the local strain (axial strain, hoop strain or off axis

strain), caused by deflections in the directions indicated by arrows 351, on the pipe 12. The

amount of change in the circumference is variously determined by the hoop strength of the

5   pipe 12, the internal pressure P_{in}, the external pressure P_{out} outside the pipe 12, the thickness

T_w of the pipe wall 352, and the rigidity or modulus of the pipe material. Thus, the thickness

of the pipe wall 352 and the pipe material in the sensor sections 14,16 (Fig. 1) may be set

based on the desired sensitivity of filter 33 and other factors and may be different from the

wall thickness or material of the pipe 12 outside the sensing regions 14,16.

10   Still with reference to Fig. 13 and Fig. 1, if an accelerometer is used as one or more

of the pressure sensors 18-24 (Figs. 14-20), it may measure the unsteady (or dynamic or ac)

pressure variations P_{in} inside the pipe 12 by measuring the acceleration of the surface of

pipe 12 in a radial direction, as represented by arrows 350. The acceleration of the surface

of pipe 12 is measured at the location of the accelerometer as the internal pressure P_{in}

15   changes and thus measures the local elastic dynamic radial response of the wall 352 of the

pipe. The magnitude of the acceleration is variously determined by the hoop strength of the

pipe 12, the internal pressure P_{in}, the external pressure P_{out} outside the pipe 12, the thickness

T_w of the pipe wall 352, and the rigidity or modulus of the pipe material. Thus, the thickness

of the pipe wall 352 and the pipe material in the sensor sections 14,16 (Fig. 1) may be set

20   based on the desired sensitivity of filter 33 and other factors and may be different from the

wall thickness or material of the pipe 12 outside the sensing region 14. Alternatively, the

pressure sensors 18-24 may comprise a radial velocity or displacement measurement device

capable of measuring the radial displacement characteristics of wall 352 of pipe 12 in

response to pressure changes caused by unsteady pressure signals in the pipe 12.

25   Referring to Figs. 14,15,16, if an optical strain gage is used, the ac pressure sensors

18-24 may be configured using an optical fiber 300 that is coiled or wrapped around and

attached to the pipe 12 at each of the pressure sensor locations as indicated by the coils or

wraps 302,304,306,308 for the pressures P_1,P_2,P_3,P_4, respectively. The fiber wraps 302-308

are wrapped around the pipe 12 such that the length of each of the fiber wraps 302-308

30   changes with changes in the pipe hoop strain in response to unsteady pressure variations

within the pipe 12 and thus internal pipe pressure is measured at the respective axial

location. Such fiber length changes are measured using known optical measurement

techniques as discussed hereinafter. Each of the wraps measures substantially the

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circumferentially averaged pressure within the pipe 12 at a corresponding axial location on the pipe 12. Also, the wraps provide axially averaged pressure over the axial length of a given wrap. While the structure of the pipe 12 provides some spatial filtering of short wavelength disturbances, we have found that the basic principle of operation of the

5   invention remains substantially the same as that for the point sensors described hereinbefore.

Referring to Fig. 14, for embodiments of the present invention where the wraps 302,304,306,308 are connected in series, pairs of Bragg gratings (310,312), (314,316), (318,320), (322,324) may be located along the fiber 300 at opposite ends of each of the

10   wraps 302,304,306,308, respectively. The grating pairs are used to multiplex the pressure signals P_1,P_2,P_3,P_4 to identify the individual wraps from optical return signals. The first pair of gratings 310,312 around the wrap 302 may have a common reflection wavelength λ_1, and the second pair of gratings 314,316 around the wrap 304 may have a common reflection wavelength λ_2, but different from that of the first pair of gratings 310,312. Similarly, the

15   third pair of gratings 318,320 around the wrap 306 have a common reflection wavelength λ_3, which is different from λ_1,λ_2, and the fourth pair of gratings 322,324 around the wrap 308 have a common reflection wavelength λ_4, which is different from $\lambda_1,\lambda_2,\lambda_3$.

Referring to Fig. 15, instead of having a different pair of reflection wavelengths associated with each wrap, a series of Bragg gratings 360-368 with only one grating

20   between each of the wraps 302-308 may be used each having a common reflection wavelength λ_1.

Referring to Figs. 14 and 15 the wraps 302-308 with the gratings 310-324 (Fig. 14) or with the gratings 360-368 (Fig. 15) may be configured in numerous known ways to precisely measure the fiber length or change in fiber length, such as an interferometric,

25   Fabry Perot, time-of-flight, or other known arrangements. One example of time-of-flight (or Time-Division-Multiplexing; TDM) would be where an optical pulse having a wavelength is launched down the fiber 300 and a series of optical pulses are reflected back along the fiber 300. The length of each wrap can then be determined by the time delay between each return pulse.

30   While the gratings 310-324 are shown oriented axially with respect to pipe 12, in Figs. 14,15, they may be oriented along the pipe 12 axially, circumferentially, or in any other orientations. Depending on the orientation, the grating may measure deformations in the pipe wall 352 with varying levels of sensitivity. If the grating reflection wavelength

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varies with internal pressure changes, such variation may be desired for certain configurations (e.g., fiber lasers) or may be compensated for in the optical instrumentation for other configurations, e.g., by allowing for a predetermined range in reflection wavelength shift for each pair of gratings. Alternatively, instead of each of the wraps being

5   connected in series, they may be connected in parallel, e.g., by using optical couplers (not shown) prior to each of the wraps, each coupled to the common fiber 300.

Referring to Fig. 16, alternatively, the sensors 18-24 may also be formed as individual non-multiplexed interferometric sensor by wrapping the pipe 12 with the wraps 302-308 without using Bragg gratings where separate fibers 330,332,334,336 may be fed to

10   the separate wraps 302,304,306,308, respectively. In this particular embodiment, known interferometric techniques may be used to determine the length or change in length of the fiber 10 around the pipe 12 due to pressure changes, such as Mach Zehnder or Michaelson Interferometric techniques such as those set forth in US Patent Application Serial No. 09/726,059, titled "Method and Apparatus for Interrogating Fiber Optic Sensors " filed

15   November 29, 2000.

The interferometric wraps may be multiplexed such as is described in Dandridge, et al, "Fiber Optic Sensors for Navy Applications", IEEE, Feb. 1991, or Dandridge, et al, "Multiplexed Interferometric Fiber Sensor Arrays", SPIE, Vol. 1586, 1991, pp176-183. Other techniques to determine the change in fiber length may be used. Also, reference

20   optical coils (not shown) may be used for certain interferometric approaches and may also be located on or around the pipe 12 but may be designed to be insensitive to pressure variations.

Referring to Figs. 17 and 18, instead of the wraps 302-308 being optical fiber coils wrapped completely around the pipe 12, the wraps 302-308 may have alternative

25   geometries, such as a "radiator coil" geometry (Fig 17) or a "race-track" geometry (Fig. 18), which are shown in a side view as if the pipe 12 is cut axially and laid flat. In this particular embodiment, the wraps 302-208 are not necessarily wrapped 360 degrees around the pipe, but may be disposed over a predetermined portion of the circumference of the pipe 12, and have a length long enough to optically detect the changes to the pipe circumference. Other

30   geometries for the wraps may be used if desired. Also, for any geometry of the wraps described herein, more than one layer of fiber may be used depending on the overall fiber length desired. The desired axial length of any particular wrap is set depending on the

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characteristics of the ac pressure desired to be measured, for example the axial length of the pressure disturbance caused by a vortex to be measured.

Referring to Figs. 19 and 20, embodiments of the present invention include configurations wherein instead of using the wraps 302-308, the fiber 300 may have shorter

5   sections that are disposed around at least a portion of the circumference of the pipe 12 that can optically detect changes to the pipe circumference. It is further within the scope of the present invention that sensors may comprise an optical fiber 300 disposed in a helical pattern (not shown) about pipe 12. As discussed herein above, the orientation of the strain sensing element will vary the sensitivity to deflections in pipe wall 352 caused by unsteady

10   pressure transients in the pipe 12.

Referring to Fig. 19, in particular, the pairs of Bragg gratings (310,312), (314,316), (318,320), (322,324) are located along the fiber 300 with sections 380-386 of the fiber 300 between each of the grating pairs, respectively. In that case, known Fabry Perot (resonator, cavity, interferometer or other known Fabry Perot arrangement), interferometric, time-of-

15   flight or fiber laser sensing techniques may be used to measure the strain in the pipe.

Referring to Fig. 20, alternatively, individual gratings 370-376 may be disposed on the pipe and used to sense the unsteady variations in strain in the pipe 12 (and thus the unsteady pressure within the pipe) at the sensing locations. When a single grating is used per sensor, the grating reflection wavelength shift will be indicative of changes in pipe

20   diameter and thus pressure.

Any other technique or configuration for an optical strain gage may be used. The type of optical strain gage technique and optical signal analysis approach is not critical to the present invention, and the scope of the invention is not intended to be limited to any particular technique or approach.

25   For any of the embodiments described herein, the pressure sensors, including electrical strain gages, optical fibers and/or gratings among others as described herein, may be attached to the pipe by adhesive, glue, epoxy, tape or other suitable attachment means to ensure suitable contact between the sensor and the pipe 12. The sensors may alternatively be removable or permanently attached via known mechanical techniques such as

30   mechanical fastener, spring loaded, clamped, clamshell arrangement, strapping or other equivalents. Alternatively, the strain gages, including optical fibers and/or gratings, may be embedded in a composite pipe. If desired, for certain applications, the gratings may be detached from (or strain or acoustically isolated from) the pipe 12 if desired.

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It is also within the scope of the present invention that any other strain sensing technique may be used to measure the variations in strain in the pipe, such as highly sensitive piezoresistive, electronic or electric, strain gages attached to or embedded in the pipe 12. Referring to Fig. 29 different known configurations of highly sensitive

5   piezoresistive strain gages are shown and may comprise foil type gages. Referring to Fig. 30 an embodiment of the present invention is shown wherein pressure sensors 18, 20, comprise strain gages 203. In this particular embodiment strain gages 203 are disposed about a predetermined portion of the circumference of pipe 12. The axial placement of and separation distance X_1 between pressure sensors 18, 20 are determined as described

10   hereinabove. In particular, the placement is dependent upon the characteristics of the ac pressure desired to be measured, for example the spatial (axial or transverse) length and coherence length of the pressure disturbance caused by the vortex, or unsteady pressure disturbance, to be measured.

       Referring to Fig. 10, there is shown an embodiment of the present invention

15   comprising three spatial filters, 33,35,37 each comprising a pair of pressure sensors measuring at total of six unsteady pressures P_1-P_6 (three pairs), each pressure sensor being a plurality (e.g., 10 meters) of fiber optic wraps and the sensors being evenly axially spaced at 1.8 inches apart, on a pipe having an inner diameter of 3.0 inches, a wall thickness of 0.22 inches and made of J55 steel production tubing, is shown. The three spatial filters, 33,35,37

20   provide spatially filtered ac pressure signals P_{as1}, P_{as2}, P_{as3}, respectively.

       These ac pressure signals P_{sa1}, P_{as2}, P_{as3} may be used as input to a variety of devices and used as desired. It is within the scope of the present invention that any number of spatial filters and spatial time filters may be used and that the particular embodiment will dictate the quantity and the spacing (not shown in Fig. 10) between each spatial filter. It is

25   noted that although pressure sensors P_1–P_6 are shown as point sensors it is within the scope of the present invention that the sensors comprise any configuration capable of accurately detecting pressure changes in pipe 12 including fiber optic wraps as described herein.

       Referring to Fig. 11, for the configuration of Fig 10, and for a liquid flow mixture of 100% oil at 111.2 gal/minute (or about 5.05 ft/sec for a 3 inch pipe), the invention provides

30   cross-correlation curves 130,132,134. The curves 130,132,134 correspond to velocities of 5.538 ft/sec, 5.541 ft/sec, 5.5822 ft/sec, for the cross-correlation between P_{sa1} and P_{as2} (vel-a), P_{as2} and P_{as3} (vel-b), and P_{as1} and P_{as3} (vel-c), for the groups of sensors a,b,c, respectively, shown in Fig. 10.

Referring to Fig. 12, it is shown that the present invention will work over a wide range of oil/water mixtures. In particular, the first two pairs of sensors (P_1,P_2, and P_3,P_4) of Fig. 10 measured the velocity at various flow rates against a reference velocity value. Data points 151-162 are groupings of measured velocity data points derived from the sensors (P_1,P_2,P_3,P_4) and are plotted against a reference velocity line 150. The data points 151-162 also show the invention will work for fluid flowing in either direction in the pipe 12. The negative flow data points 151-158 were taken with a fluid of 100% oil and the positive flow data points 159-162 were taken over a range of various oil/water mixtures. Specifically, data points 159 represent 100 individual data points taken at velocities from about 5.2 ft/sec to about 5.7 ft/sec and in oil/water mixtures from 0% to 100% water. Data point 160 represents a single individual data point taken at a velocity of about 9.9 ft/sec in an oil/water mixture of 0% water. Data point 161 represents a single individual data point taken at velocity of about 13.7 ft/sec in an oil/water mixture of 0% water. Similarly, data points 162 represent 21 individual data points taken at velocities from about 18.0 ft/sec to about 19.0 ft/sec and in oil/water mixtures from 0% to 100% water. The departure of the raw data 151-162 from the reference velocity line 150 is caused, in part, by the fact that the points were not calibrated and that the reference velocity at each point was taken manually by a technician. Had the data points been calibrated and electronically matched to the sensed points the departure from the reference line 150 would not have been as large as depicted in the figure.

The present invention will also work over a wide range of multiphase fluid mixtures. Also, the invention will work for very low flow velocities, e.g., at or below 1 ft/sec (or about 20.03 gal/min, in a 3 inch diameter ID pipe) and has no maximum flow rate limit. Further, the invention will work with the pipe 12 being oriented vertical, horizontal, or any other orientation. Also the invention will work equally well independent of the direction of the flow along the pipe 12.

Referring to Fig. 21, instead of the unsteady pressure sensors 18,20 and the corresponding unsteady pressure signals P_1,P_2 being spaced axially along the pipe 12, the sensors 18,20 may be spaced circumferentially apart at substantially the same axial location. In that case, the spatial filter 33(Fig. 1) (i.e., the difference between the two signals P_1, P_2, P_3,P_4) filters out substantially all one dimensional acoustic waves propagating through the sensing region 14.

Alternatively, referring to Fig. 22, instead of the pressure sensors 18,20 being located directly across from each other, the signal P_2 may be measured at a distance circumferentially closer to the sensor 18, as indicated by a sensor 200. The circumferential distance 53 between the two sensors 18,200 should be large enough to independently

5   measure a propagating vortical pressure field 15 such that the spatial filter 33 output is not zero for the measured vortex 15, i.e., that the circumferential distance 53 is greater than the transverse spatial length of vortex 15. In addition, the distance X_1 (Fig. 1) should be less than or equal to the axial coherence length of the vortex 15 such that the spatial filter output is indicative of a measured vortex 15.

10   The thickness and rigidity of the outer wall of the pipe 12 is related to the acceptable spacing X_1 (Fig. 1) between the sensors 18,20 of the spatial filter 33. More specifically, the thinner or less rigid the pipe 12 wall, the closer the sensors 18,20 can be to each other.

Also, for optimal performance, the distance X_1 between the two sensors 18,20 should be larger than the spatial length of the vortical pressure field 15 such that each of the

15   sensors 18,20 can independently measure the propagating vortical pressure field 15 between the sensors 18,20 at different times (such that the spatial filter 33 output is not zero for the measured vortex 15). Also, the distance X_1 should be within the coherence length of the vortex 15 such that the spatial filter output is indicative of a measured vortex 15. Also, for optimal performance, the overall length L_1 between the first sensor 18 and the last sensor 24

20   of the velocity sensing section should be within the coherence length of the vortices 15 desired to be measured. The coherence length of the vortical flow field 15 is the length over which the vortical flow field remains substantially coherent, which is related to and scales with the diameter of the pipe 12.

Vortices that are sensed by only one of the spatial filters, because either a vortex is

25   generated between the spatial filters or generated outside the spatial filters and decay between them, will be substantially random events (in time and location) that will not be correlated to the vortices that are sensed by and continuously occurring past both spatial filters and, as such, will not significantly affect the accuracy of the measurement.

Referring to Fig. 24, a particular embodiment of the present invention is shown

30   therein where more than two sensors may be used for one or both of the spatial filters 33,35. In particular, the summer 44 may have three inputs P_1, P_2, P_3, from three pressure sensors 220,222,224 where the output signal $P_{sa1} = P_1 - 2P_2 + P_3$. For optimal performance, the overall axial length L of the filter 33 should be within the coherence length of the vortices 15 being

measured and the individual spacing between the sensors 220,222,224 should have the same criteria discussed hereinbefore for the spacing between two sensors 18,20.

Referring to Fig 32, instead of using four pressure sensors to make the spatial filters 33,35 three pressure sensors 600,602,604 may be used where the middle sensor 602 is used for both the spatial filters 33,35.

Referring to Figs. 28-31, instead of measuring the unsteady pressures P_1-P_4 on the exterior of the pipe 12, the invention will also work when the unsteady pressures are measured inside the pipe 12. In particular, the pressure sensors 18,20 that measure the pressures P_1,P_2, may be located anywhere within the pipe 12, having the same constraints discussed hereinbefore for the exterior measurements. Any technique may be used to measure the unsteady pressures inside the pipe 12.

Referring to Figs. 25-27, the invention may also measure the velocity of flow outside a pipe or tube 400. In that case, the tube 400 may be placed within the pipe 12 and the pressures P_1-P_4 measured at the outside of the tube 400. Any technique may be used to measure the unsteady pressures P_1-P_4 outside the tube 400.

Referring to Fig. 25, for example, the tube 400 may have the optical wraps 302-308 wrapped around the tube 400 at each sensing location. Alternatively, any of the strain measurement or displacement, velocity or accelerometer sensors or techniques described herein may be used on the tube 400. Referring to Fig. 26, alternatively, the pressures P_1-P_4 may be measured using direct pressure measurement sensors or techniques described herein. Any other type of unsteady pressure sensors 18-24 may be used to measure the unsteady pressures within the pipe 12.

Alternatively, referring to Fig. 27, hydrophones 402-408 may be used to sense the unsteady pressures within the pipe 12. In that case, the hydrophones 402-408 may be located in the tube 400 for ease of deployment or for other reasons. The hydrophones 402-408 may be fiber optic, electronic, piezoelectric or other types of hydrophones. If fiber optic hydrophones are used, the hydrophones 402-408 may be connected in series or parallel along the common optical fiber 300.

The tube 400 may be made of any material that allows the unsteady pressure sensors to measure the pressures P_1-P_4 and may be hollow, solid, or gas filled or fluid filled. One example of a dynamic pressure sensor is described in co-pending commonly-owned US Patent No. 6,233,374, entitled "Mandrel Wound Fiber Optic Pressure Sensor". Also, the end 422 of the tube 400 may be closed or open. If the end 422 is closed, the flow path

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would be around the end 422 as indicated by lines 424. If the end 422 is open, the flow path would be through the inside of the tube, as indicated by a line 426 and the pressure would be measured inside of the pipe 12. For harsh environment industrial applications, the tube 400 may be coiled tubing having the pressure sensors for sensing P_1-P_4 inside the tubing 400.

Although the invention has been described with respect to the detection of certain types of unsteady flow fields and the pressure disturbances associated therewith, it should be understood that the invention will also detect any unsteady stochastic flow field and its associated pressure field that propagates within the flow, provided the spatial filters have a separation within the acceptable coherence length of the flow field to be measured and the sensor spacing within each spatial filter is longer than a characteristic spatial length of the disturbance. Some examples of such other stochastic flow fields are gas bubbles, gas slugs, particles, or chunks of material, which may travel in the flow at different rates than the mean flow velocity, thereby creating a traveling pressure disturbance, which exhibits a velocity slip between it and the other constituents in the mixture.

Accordingly, the invention may be used to detect such different flow rates within the same mixture (e.g., the flow rate of an unsteady pressure field within the mixture). Also, such unsteady flow fields, when traveling at different rates from other portions of the mixture, may also shed vortices in the flow that may propagate with the flow and be detected as an unsteady flow field by the present invention.

Referring to Fig. 33, there is shown an embodiment of the present invention in a typical industrial processing application, the sensing section 51 may be connected to or part of process tubing 502 (analogous to the pipe 12 in the test section 51) within an industrial process control system 500. The isolation sleeve 410 may be located over the sensors 18, 20, 22, 24 as discussed hereinbefore and attached to the pipe 502 at the axial ends to protect the sensors 18, 20, 22, 24 (or fibers) from damage during deployment, use, or retrieval, and/or to help isolate the sensors from acoustic external pressure effects that may exist outside the pipe 502, and/or to help isolate ac pressures in the pipe 502 from ac pressures outside the pipe 502. The advantages and effect of the isolation sleeve 410, as well as other isolation techniques, are described in commonly owned copending US Patent Application Serial No. 09/344,070, entitled "Measurement of Propagating Acoustic Waves in Compliant Pipes" incorporated herein by reference in its entirety. The sensors 18, 20, 22, 24 are

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connected to a cable 506 which may comprise the optical fiber and is connected to a transceiver/converter 510 of the control system 500.

When optical sensors are used, the transceiver/converter 510 may be used to receive and transmit optical signals to the sensors 18-24 and provides output signals indicative of

5   the pressure P_1-P_4 at the sensors 18-24 on the lines 30-36, respectively. Also, the transceiver/ converter 510 may be part of the Velocity Logic 40. The transceiver/converter 510 may be any device that performs the corresponding functions described herein. In particular, the transceiver/ converter 510 together with the optical sensors described hereinbefore may use any type of optical grating-based measurement technique, e.g.,

10   scanning interferometric, scanning Fabry Perot, acousto-optic-tuned filter (AOTF), optical filter, time-of-flight, etc., having sufficient sensitivity to measure the ac pressures within the pipe.

A plurality of the sensors 10 of Fig. 33 of the present invention may be connected to a common cable and multiplexed together using any known multiplexing technique by

15   connecting end 511 to other sensors (not shown). For instance, it is contemplated that the various embodiments of the sensor 10 of the present invention include the capability being multiplexed as well as capable of communication with various protocols and systems currently in use in the industrial sensing area. For instance, and with reference to Fig. 33 there is shown a portion of a process control system 500 incorporating a sensor 10 in

20   accordance with the present invention. Fluid velocity logic 40 communicates signal Uc(t) along line 42 to control device 70, a computer or micro-processor for example, where the information may be used to control the fluid velocity in pipe 502 through known controls means such as a pump, valve, throttle, etc. (not shown). In certain embodiments of control system 500 and with appropriate electro-optical conversion of the sensor return signal to a

25   conventional 4-20 mA signal the signal can be combined with other control devices and sensors at control device 70 via separate electrical lines. In this particular embodiment the communication from the fiber optic sensor is performed with a 4-20 mA analog signal, and the open protocol HART®. (Highway Addressable Remote Transducer) digital communications format. Similarly, communication from the fiber optic sensor 10 may also

30   be performed with open and interoperable protocol FOUNDATION™ Fieldbus that provides a digital communication link among intelligent field level and control devices via electrical lines. The control device 70 can be configured for use with other process protocols, including Device Bus, Sensor Bus, Profibus, the ethernet, and others in use

throughout the world. The use of feedthroughs 511, as shown in Fig. 33, make the sensor 10 of the present invention uniquely qualified for industrial applications requiring multiple sensors. The use of sensors having feedthroughs in a large multi-point process enables connectivity to the multiple sensors through a single fiber optic cable. Electronic sensors of

5   the prior art require dedicated wiring to the sensor and back to the instrumentation. For instance, a typical industrial process control system that utilizes electronic flowmeters of the prior art requires an electrical process loop to facilitate both a power signal to the transmitters and bi-directional communication, and can be constructed in accordance with a number of the aforementioned process communication protocols.

10   In operation, industrial process uses for the present invention include reverse osmosis, coking, general refining uses, in-line pressure sensors for emissions monitoring, sensors for monitoring hydrogen, combustion control, gas composition analysis, distributed sensors in tank gauging, multi-phase computational fluid dynamics, instrumentation of multiphase flows, among others.

15   It should be understood that any of the features, characteristics, alternatives or modifications described regarding a particular embodiment herein may also be applied, used, or incorporated with any other embodiment described herein.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made

20   therein and thereto without departing from the spirit and scope of the present invention.

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